THE EFFECTS OF PRELOADING HISTORY ON THE UNDRAINED BEHAVIOUR OF SATURATED LOOSE SAND

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ABSTRACT

This paper presents a comprehensive analysis of the effects induced by drained and undrained preshear and, in general, by preloading history on the undrained behaviour of loose sand prepared by moist tamping. The results are interpreted from the point of view of understanding the evolution of elastic anisotropy and the shape of the yield surface. The undrained behaviour of loose sand is shown to be a powerful and expeditious means for analysing the effects of stress-induced anisotropy. At first the reliability of this approach is evaluated through a comparison of the undrained effective stress paths with the stress states corresponding to a stiffness change along drained stress paths of samples subjected to the same preloading history.

Subsequently the effects induced by isotropic preconsolidation, by drained preshear at different maximum stress ratios and along different stress paths, by undrained preshear and, finally, by drained cyclic preshear are analysed in detail on samples with similar void ratios at the beginning of the undrained loading phase; the results are discussed in terms of the evolution of the yield surface and elastic anisotropy. This paper is consequently both a further development in the analysis of the effects of preloading history on the undrained behaviour of saturated loose sand and another step towards a better understanding of the mechanisms governing the evolution of mechanical anisotropy in loose sands along triaxial stress paths.

Key words: anisotropy, liquefaction, sand, stress history, stress path, triaxial test (IGC: D6)

INTRODUCTION

In recent years the liquefaction behaviour of loose sand under static loading conditions (i.e. under a monotonically increasing undrained loading) has received a considerable amount of attention since the works by Bjerrum et al. (1961) and Castro (1969). As a result, the conditions affecting the initiation of static liquefaction and the undrained behaviour of loose saturated sands are quite well understood. The influence of initial density was first analysed by Castro (1969); Ishihara and Okada (1978b, 1982) and Vaid et al. (1989) analysed the effects induced by undrained preshear on the undrained cyclic and monotonic response of loose sand, and Krammer and Seed (1988) were the first to analyse the effects induced by an initial static shear stress on subsequent undrained behaviour.

Many authors have since worked either on these or on related topics; for instance, Canou et al. (1991) studied the reduction in the undrained shear strength of loose Hostun sand due to an initial shear stress; Mاتيotti et al. (1995) and Donah et al. (1997) analysed the effects induced by anisotropic consolidation and preconsolidation on the undrained behaviour of loose Hostun sand, both in compression and in extension; Di Prisco et al. (1995)

demonstrated the general dependence of the undrained behaviour of loose sand on its preloading history.

The research described in this paper is primarily concerned with further improving the analysis of the effects of preshear and, more in general, of the preloading history on the undrained behaviour of saturated loose sand. In particular, the effects of drained and undrained preshear and of "complex" preloading histories are presented with the primary aim of providing further experimental data on the undrained behaviour of loose sands. These data could be useful for the calibration and the reliability analysis of constitutive models intended to reproduce the undrained behaviour of granular media.

Furnishing further experimental data on the undrained behaviour of saturated loose sands is not the only aim of this paper, however: in fact, the undrained behaviour of loose saturated sands is shown to be a powerful and expeditious means for analysing the effects of preloading history on the orientation and shape of the yield surface and on the elastic anisotropy.

Unfortunately, it is impossible to obtain a complete definition of the yield locus and of the elastic behaviour from a single undrained test so, while in some cases undrained tests give precise information on yield locus and elastic behaviour, in other cases the information deduci-

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ble from the undrained behaviour is mainly qualitative and should be integrated using a different approach. In particular, the elastic behaviour can be reliably evaluated only when a stress reversal is applied, because immediately after the reversal the plastic strains are predictably negligible.

From a practical point of view, these data are expected to be useful for improving our understanding of the evolution of the mechanical properties of granular materials under loading and, as a consequence, for developing constitutive models capable of predicting even complicated loading paths, of the kind that can occur in real situations. In fact, this can only be achieved through a detailed comprehension of the evolving characteristics of the mechanical properties of granular materials.

The first part of the paper evaluates the reliability of the proposed approach for deducing the shape of the yield locus and the elastic anisotropy from the undrained behaviour of loose sand samples. This is done by comparing the undrained effective stress paths with the stress states at which a change of stiffness occurs in the stress-strain curves obtained from drained tests on samples previously subjected to the same preloading history as the undrained test samples. In this way we have assumed that the occurrence of a stiffness change along a drained stress path coincides with the occurrence of irreversible strains, according to the definition of the yield locus. These yield stresses were evaluated from the intersections of the rectilinear extrapolations of the pre- and post-yield portions of the stress-strain curves.

The second part of the paper is concerned with the analysis of the effects on subsequent undrained behaviour of the following:

- an isotropic preconsolidation;
- the maximum stress ratio applied during a drained monotonic compression preshear;
- the inclination of the stress path applied during a drained monotonic compression preshear;
- a drained monotonic extension preshear;
- an undrained monotonic compression preshear;
- a cyclic drained compression preshear.

The results are obtained on samples which have a similar density at the beginning of the undrained loading phase, in order to avoid any effects induced by a different void ratio.

Most of the results presented concern the effects induced by drained preloading histories and thus differ from the analyses presented by Ishihara and Okada (1978b, 1982) and by Vaid et al. (1989), which were concerned with the effects induced by undrained monotonic and cyclic preshear. Moreover, the results presented by Ishihara and Okada (1978b, 1982) and Vaid et al. (1989) were obtained on loose sand samples prepared by sedimentation and water pluviation, respectively, as opposed to those presented herein which were obtained on moist tamped samples. This may enable further comparison between the types of mechanical behaviour induced by the different methods of sand sample preparation.

TESTING EQUIPMENT, MATERIALS AND SAMPLE PREPARATION

The experimental research was performed in a Bishop-Wesley triaxial cell with an enlarged chamber which allowed for the testing of samples 70 mm in diameter by 140 mm in height. The end platens were frictional. Back pressure, cell pressure and ram pressure were controlled by a computer system which is capable of regulating a minimum pressure variation of about 0.06 kPa: this value permitted a very accurate test control. Digital data acquisition was performed using a sampling frequency of about 40 readings per minute for controlling the tests, whereas about 2 readings per minute were recorded. Axial load was measured by a submersible load transducer and axial strains were measured by an external displacement transducer.

The research was carried out on Hostun sand RF: this sand is a uniform ($U=2$), medium sand ($D_{50}=0.38$ mm) mainly comprising angular quartz grains (Flavigny et al., 1990). The minimum and maximum void ratios of this sand equate to 0.656 and 1.000, respectively (e.g. Canou 1989). This sand is a reference sand in many French laboratories.

Very loose sand samples were prepared following the moist-tamping technique, i.e. dry sand was mixed with 3–4% of distilled water and gently compacted in 7 layers inside a mould. A vacuum slightly lower than 100 kPa was applied, the mould was dismantled, the sample dimensions were measured and the triaxial chamber was assembled. Following a standard technique, the samples were first flushed with carbon dioxide and then percolated with de-aerated water under a cell pressure of about 100 kPa. During this phase, the volume changes occurring when water was added and due to grain structure collapse induced by water menisci breaking were evaluated from the experimental results on Hostun sand by Bahloul (1990). Finally a back-pressure of 300 kPa was applied to all triaxial samples. These procedures ensured a Skempton's pore pressure parameter B constantly greater than 0.98.

The authors found the repeatability of sample preparation and test results fairly satisfactory, especially when the samples were prepared by the same operator, as in this experimental program. Moreover it is worth noting that the repeatability of the test results was seen to increase as a result of the drained preshear applied, which seems to induce a great structural rearrangement and consequently to cancel any initial heterogeneity.

No correction for membrane penetration and system compliance was considered in the analysis of the results, so the reader should consider that a partial drainage may occur due to such compliances, which are expected to be very small, however. Let us try to evaluate the effects of such compliances from a qualitative point of view. As shown in the next sections, a preshear in one side (e.g. in compression) induces a low pore pressure before the peak deviator, by comparison with virgin samples, during subsequent undrained loading on the same side. As a

consequence, the effects of the various compliances in undrained tests on presheared samples are expected to be smaller than those of virgin samples. In particular, since membrane penetration induces a partial drainage, it is expected to reduce the difference between virgin and presheared samples in some way.

TEST RESULTS

The Relationships between the Undrained Effective Stress Path and the Occurrence of Stiffness Changes along Drained Stress Paths

In the framework of classical elastoplasticity, the descending part of the undrained effective stress path of a saturated loose sand which undergoes complete liquefaction is expected to lie close to the yield surface. Therefore the undrained effective stress path is expected to be similar, at least from a certain point onwards (i.e. in the descending part), to the yield surface (e.g. Mاتيotti et al., 1995). On the other hand, in recent constitutive models based on the bounding surface approach or on hypoplasticity, the elastic domain is considered either very small or even entirely negligible. Therefore, the descending part of the undrained stress path in these models may be completely unrelated to the shape of a yield surface, as intended in classical elastoplasticity.

To the authors' knowledge, Ishihara and Okada (1978a) were the first to deduce the shape of the yield surface from the analysis of the undrained effective stress path of overconsolidated loose sand samples. In particular they assumed that the change in the inclination of the effective stress path coincides with the intersection of the stress path with the yield surface and they observed that an isotropic consolidation induces an isotropic expansion of the yield surface. The preparation method and the initial density of the samples investigated by Ishihara and Okada (1978a) led to the final dilative behaviour of the undrained tests, without the final softening phase typical

of complete liquefaction.

It is therefore interesting to investigate the physical meaning of the descending part of the undrained effective stress path of a saturated loose sand sample which undergoes complete liquefaction by comparing the undrained effective stress path with the stress states where a stiffness change occurs along drained stress paths. In this way we assume that the occurrence of a stiffness change along a drained stress path coincides with the occurrence of irreversible strains, according to the definition of yield locus. Some samples were therefore loaded along a conventional drained compression path up to $q_{\max}=100$ kPa starting from $p'=100$ kPa, then unloaded to $q=0$ and finally reloaded under drained conditions, both in extension and in compression, along the effective stress paths shown in Fig. 1(a). The stress states representing the stiffness change in the stress-strain behaviour (Fig. 1(b)) were compared with the undrained effective stress paths of two samples which were subjected, for the undrained compression, to the same previous stress history ($q_{\max}=100$ kPa) and, for the undrained extension to a similar stress history ($q_{\max}=150$ kPa). We are thus anticipating here the effects induced by previous preshear on undrained effective stress paths, but a complete description of such effects will be presented in subsequent sections. Figure 1(a) shows the comparison between undrained effective stress paths and the position of the stiffness change in the stress-strain behaviour of the samples subjected to a drained stress path; Fig. 1(b) shows the stress-strain behaviour. The samples loaded on the compression side present a sharp stiffness change, whereas the sample loaded in the extension side has a much smoother stiffness change. The symbols of Figs. 1(a) and 1(b) coincide and mark the position of the stiffness change in the stress-strain behaviour.

From the comparison it can be concluded that, especially for the compression side, the descending part of the undrained stress path is close to the points at which

Fig. 1. Comparison between the undrained effective stress paths and the stress states where a stiffness change occurs along a drained loading path

there is a sharp stiffness change along a drained loading (which is assumed to coincide with the occurrence of plastic strains, i.e. with the yield surface as defined in the classical theory of elastoplasticity); in other words the descending part of the undrained stress path can be considered close to a classical yield surface characterised by a finite size, the position of which is slightly affected by drained unloading. On the other hand, the stiffness change on the extension side is much smoother and the existence of a well defined yield point is questionable. The tentative shape of the yield surface resulting from the drained preshear is illustrated in Fig. 1(a): this shape was inspired by the one proposed by Yasufuku et al. (1991).

These experimental observations are therefore useful for the correct definition of modern constitutive models which generally try to represent a continuous and smooth variation in stiffness (which is typical of the first loading of granular media), but which might fail to represent the reloading phase. Moreover these considerations are useful for the analysis of the results described in subsequent sections, which attempt to analyse the evolution of the stress-induced anisotropy and of the yield surface.

The Effects of Isotropic Preconsolidation

Ishihara and Okada (1978a) were the first to carry out a detailed experimental analysis on the effects of isotropic preconsolidation on the undrained behaviour of a loose sand prepared by sedimentation in water. They observed that overconsolidation induces isotropic expansion of the yield surface.

Since the analysis performed by Ishihara and Okada (1978a) was carried out on samples which were not undergoing complete liquefaction, for the sake of completeness, we take a quick look here at the effects of isotropic preconsolidation on a moist tamped sample, which undergoes complete liquefaction. Figures 2(a) and 2(b) show the undrained effective stress paths and the stress-strain behaviour of three samples, one of which had previously

been isotropically consolidated up to $p'_{\max}=320$ kPa and then unloaded to $p'=100$ kPa ($OCR=3.2$) and the others were normally consolidated ($OCR=1.0$). The influence of the initial void ratio ($e=0.89$ and $e=0.93$) can be deduced from a comparison of the results with the two normally consolidated samples: the peak deviator stress increases slightly (13%) due to the increase in density. In Fig. 2, at the beginning of the undrained loading the overconsolidated sample had a void ratio ($e=0.91$) similar to the others and thus the differences observed between the undrained effective stress paths are due only to isotropic preconsolidation. The stress path of the preconsolidated sample is roughly vertical up to a higher deviator stress with respect to the other samples, which were not preconsolidated. This is consistent with the observation by Ishihara and Okada (1978a). Moreover, the peak deviator stress of the preconsolidated sample is about 35–40% larger than that of the other samples. The differences observed in terms of peak deviator stress can be attributed to an enlargement (probably homothetic) of the yield surface induced by the preconsolidation (as usually assumed in the classical theory of plasticity and as observed also by Ishihara and Okada, 1978a) and to the later onset of plastic volumetric strains in the overconsolidated sample than in the samples which were not preconsolidated. The fact that the undrained effective stress path is initially fairly vertical involves an initial elastic isotropy, if the initial plastic strains are assumed to be negligible. As a result, we can deduce that isotropic preconsolidation reduces the anisotropy of the initial fabric (as observed by Rowe, 1971) or leaves an initial isotropic fabric substantially unchanged (as might be expected in this case, due to the moist tamping preparation).

The Effects of Drained Monotonic Compression Preshear

The effects induced on undrained behaviour by an initial static shear stress and by anisotropic consolidation

Fig. 2. The effects induced by isotropic preconsolidation on undrained behaviour

were examined by Kramer and Seed (1988), Canou et al. (1991), Matioti et al. (1995) and Donah et al. (1997). These authors have shown that the instability line defined by Lade et al. (1988) or the collapse surface defined by Sladen et al. (1985) must be considered dependent on the previous stress history. In the above-mentioned works, the samples were loaded to a given stress state under drained conditions and then the drainage valve was closed and the samples were subsequently loaded under undrained conditions. This was intended to analyse the undrained behaviour which could occur in a real situation, in which the initial stress state is not isotropic.

In this work, in order to highlight the effects of previous preshear along the whole undrained effective stress path, all the samples were loaded along a drained compression stress path starting from $p' = 100$ kPa up to different stress states ranging between $q_{\max} = 30$ and $q_{\max} = 150$ kPa (corresponding to $\phi_{mob} = 7.5^\circ$ and $\phi_{mob} = 25.4^\circ$, respectively); then they were unloaded to $q = 0$ and, at the isotropic state of stress, the drainage valve was closed and the samples were subjected to undrained loading. Care was taken to have similar void ratios at the beginning of the undrained loading phase. For the sake of comparison, one sample (Test a12 in Fig. 3) was subjected to the test performed by Kramer and Seed (1988): at the maximum preshear ($q_{\max} = 150$ kPa in this case) the drainage valve was closed and the sample was sheared under undrained conditions.

Figure 3(a) shows the undrained stress paths obtained after drained preshear up to different stress ratios along a conventional triaxial compression path (under a constant cell pressure). It can be observed that previous preshear induces an important increase in the maximum deviator stress and a considerable displacement of the descending part of the undrained effective stress path. Moreover the initial part of the undrained stress path is inclined towards the positive p' -axis and, if an initial elastic behav-

iour is assumed, this means that there is an initial anisotropic elasticity with a greater stiffness in the vertical direction (Graham and Houlsby, 1983). The assumption that the behaviour is initially elastic at the beginning of undrained reloading is justified by the reverse in loading direction applied, which is expected to make the state of stress enter the yield surface. The initial elastic anisotropy does not seem to be much affected by the maximum applied preshear.

In Fig. 3(a) it is worth noting that, in the phase preceding the peak shear stress, the undrained effective stress path of the sample subjected to the largest stress ratio during preshear (i.e. $q_{\max} = 150$ kPa) bends in the direction of the positive p' -axis as the elastic anisotropy increases. From this result we can try to deduce to what degree the anisotropy is stress- and strain-induced. In fact, we know that mechanical anisotropy is induced by two effects: the first relating to the re-orientations of the normals to the intergranular contacts, which is affected mainly by plastic strains, and the second connected to the direction of intergranular contact forces, which is affected by the state of stress. Since the plastic strains are probably small during the unloading-reloading phase, the changes in fabric are small too and, as a result, the decrease and subsequent increase in anisotropy are connected mainly to the re-orientation of the intergranular forces. Therefore the anisotropy induced by the drained preshear is partly lost during the drained unloading, but is shortly regained during the subsequent undrained reloading. The decrease and subsequent increase in anisotropy during drained unloading and undrained reloading are, in any case, much smaller than those induced during the first drained loading. As a result, the anisotropy induced during drained preshear is probably connected more to the strain than to the applied stress. In Fig. 3(b), it is worth noting the small hysteresis loop between drained unloading and the subsequent undrained reloading, where the stress-strain behav-

Fig. 3. The effects induced by drained compression preshear at different maximum deviator stresses on undrained behaviour

our is shown.

Figure 3(a) prompts the deduction that the yield surface undergoes extensive stretching towards the compression side. In particular, the samples presheared up to $q_{\max} > 100$ kPa (corresponding to a mobilised friction angle greater than $\phi_{\text{mob}} > 19.5^\circ$) seem to be characterised by a yield surface which keeps trace of the previous maximum preshear stress (see also Fig. 1(a)). In fact, the undrained stress paths seem to lie on a surface passing through the previous maximum applied drained deviator stress state, as shown by Poorooshasb et al. (1966, 1967) and Tatsuoka and Ishihara (1974), who detected mildly curved yield loci. Both the undrained effective stress path and the maximum applied deviator stress lie on the undrained stress path of the sample which was subjected to undrained loading starting from the maximum applied shear stress (Test *a12*). Within the yield surface the elastic deformations are anisotropic, as we can see from the initial inclination of the undrained effective stress path. Finally the sharp bend in the effective stress path of the sample subjected to a maximum deviator stress of $q_{\max} = 150$ kPa is consistent with the sudden onset of plastic strains observed in Fig. 1(b) under drained loading.

It is worth observing that the samples reach a final steady state, with a stress state lying on a common line on the q - p' plot, i.e. the stress ratio and thus the mobilised steady state friction angle are the same (about $\phi_{ss} = 30^\circ$). However, though the void ratios are very similar, the final stress states at the steady state are strongly affected by the previous preshear and, as a result, the final states will not lie on the same line in the e - p' plot; in fact the final states have approximately the same ordinate (e), but different abscissa (p'). In other words, the presheared samples seem to behave as if they were denser than the others. The same conclusion was drawn by Vaid et al. (1989) from the behaviour of undrained presheared loose

samples. A non-unique line in e - p' plot would contradict the concept of unique steady state which was proved valid by Negussey and Islam (1994) for isotropically and anisotropically consolidated compression tests.

However, following the observation by Desrues et al. (1996) on the possible non-uniformity of the strain field in samples tested with unlubricated end platens, the differences in terms of the stress state at the steady states observed in Fig. 3 can probably be attributed to a different heterogeneity in terms of stress and strain distribution at the steady state of the presheared samples with respect to the virgin sample.

Figures 4(a) and 4(b) show the effects induced by different inclinations of the stress paths (defined in the figures with the ratio $\Delta q / \Delta p'$ of the drained loading path), for a constant maximum applied stress ratio ($q/p' = 0.75$, corresponding to a mobilised friction angle of $\phi_{\text{mob}} = 19.5^\circ$). Clearly, the inclination of the drained stress path during preshear has a strong influence on the subsequent undrained behaviour. Unfortunately, the initial inclination of the effective stress path at p' -axis is not always indicative; in fact, if the initial part of the undrained stress path is inclined towards the positive p' -axis, as mentioned previously, it can be deduced that the sample is stiffer in the vertical direction and that the elastic behaviour is anisotropic. On the other hand, an initial inclination of the effective stress path towards the negative p' -axis can be attributed to both a greater stiffness in the horizontal direction (i.e. to an anisotropic elasticity) and to the occurrence of plastic strains (thus disregarding the possibility of a non-linear elasticity). Thus a drained preshear with a stress path inclined towards the negative p' -axis gives either a different stretching of the yield surface (which induces greater initial plastic strains) or an elastic anisotropy with a greater stiffness in the horizontal direction. The decreasing part of the undrained stress path is

Fig. 4. The effects induced by drained compression preshear along different stress paths on undrained behaviour (the plotting of the preshearing phase of the Test *11pan* is prematurely terminated in order to maintain an appropriate graphical scale)

also affected by the inclination of the stress path during previous preshear, revealing that the evolution of the yield surface is affected by both the applied maximum stress ratio and the drained stress path during preshear as well. In conclusion, therefore, considering drained compression preshears with an equal maximum stress ratio q/p' , the preshear obtained by increasing the vertical effective stress (i.e. inclined towards the positive p' -axis) does not lead to the same anisotropy as is obtained by decreasing the horizontal effective stress (i.e. inclined towards negative p' -axis).

It is worth noting that the sample named *ani1* of Fig. 3 remained for about 15 hours in an isotropic state of stress ($p'=100$ kPa and $q=0$ kPa) after being presheared and before being subjected to the undrained loading, whereas all the other samples were loaded under undrained conditions immediately after being subjected to the drained unloading. After the said 15-hour interval, the undrained behaviour of sample *ani1* appeared substantially unchanged and it can therefore be concluded that permanence in the isotropic state of stress after drained preshear for the said period of time does not affect the subsequent undrained effective stress path and consequent induced anisotropy.

Finally, the effects of drained compression preshear on undrained extension stress paths are examined in Fig. 5: the effects on the extension side can be seen to be quite large, but relatively small by comparison with those induced on the compression side. This is similar to the behaviour observed by Ishihara and Okada (1978b) on samples subjected to a "small" undrained preshear (i.e. to a stress ratio less than the one corresponding to the line of phase transformation, which for Hostun sand could be expected at an angle of about $\phi=30^\circ$): a small undrained preshear in one side (e.g. extension) was seen to induce a negligible effect on undrained loading on the other side (e.g. compression). Figure 5 shows that the undrained behaviour on the extension side, which follows the drained

preshear on the compression side, seems to be more compressive than that of the virgin sample and this is consistent with the results reported by Lanier et al. (1991) who observed an increased volumetric compressibility on the extension side after preshearing the sample to a very great axial strain on the compression side (up to $\varepsilon_a=10-25\%$, whereas in our tests $\varepsilon_a=3\%$ at most).

In conclusion, the drained compressive preshear induces severe stretching of the yield surface towards the compression side, while the shape of the yield surface on the extension side is scarcely affected (as tentatively shown in Fig. 1(a)). The stretching of the yield surface, and probably also the elastic anisotropy, are affected by the inclination of the stress path followed during the drained preshear.

The Effects of Drained Monotonic Extension Preshear

The effects induced by drained extension preshear on the subsequent undrained effective stress paths in extension and compression are shown in Fig. 6. The minimum drained preshear was $q_{\min} = -60$ kPa (which corresponds to a mobilised friction angle of $\phi=16^\circ$). The results are similar to those of the previous section: the effects of previous drained extension preshear are large on undrained extension tests, leading to an important decrease in minimum deviator stress, whereas they are much less on the compression side (although the results are not directly comparable with each other because the initial mean effective stress for sample *a11* was slightly greater than for the others). This kind of behaviour is consistent with the situation observed in the previous section concerning the effects of drained compression preshear. Moreover, it is worth noting that the inclination of the undrained stress path of the presheared sample (Test *a19*, $q_{\min} = -60$ kPa) is vertical up to a large stress ratio and thus, after preshearing, if the behaviour at the beginning of undrained reloading is assumed to be elastic, the sample has an initial isotropic elasticity. This is not consis-

Fig. 5. The effects induced by drained compression preshear on undrained behaviour

Fig. 6. The effects induced by drained extension preshear on undrained behaviour

tent with the results of the compression tests shown in the previous section (*see*, for instance, Test *ani3* of Fig. 4(a), which was presheared up to a similar mobilised friction angle) and probably has to do with the fact that the initial anisotropy of a sample prepared by moist tamping is probably not negligible; in fact the anisotropy induced by the extension preshear can only decrease the initial anisotropy leading to the observed isotropic elasticity.

Figure 7 shows how extension preshear can affect the anisotropy previously induced by a drained compression preshear: this result may help us to understand the amount of extension preshear needed to erase the effects of a compression preshear. The maximum compression and extension drained deviator stresses were $q_{max}=150$ kPa and $q_{min}=-60$ kPa, respectively, and, at the beginning of undrained loading, the residual axial strain was fairly small $\epsilon_a=-0.15\%$ and the void ratio was $e=0.88$. The undrained effective stress path shown in Fig. 7(a) shows that the drained extension preshear applied does not restore the initial conditions of the virgin sample; in fact, the undrained peak deviator of the presheared sample is considerably higher than that of a virgin sample, although the void ratios at the beginning of undrained loading are similar ($e=0.88$ and $e=0.89$). The application of both a compression and an extension drained preshear seems to induce the same effects as an isotropic preconsolidation, with an apparent enlargement of the yield surface. This is consistent with the observation that a drained preshear on one side (e.g. extension) mainly affects the behaviour on the same side and leaves the behaviour on the other side virtually unchanged (e.g. compression).

In conclusion, the evolution of the yield surface on the extension side is similar to the one on the compression side, whereas the elastic anisotropy induced by a drained extension preshear is much less than is induced on the

compression side.

The Effects of Undrained Monotonic Compression Preshear

The effects induced by an undrained preshear on sedimented and pluviated sand samples, respectively, were examined in detail by Ishihara and Okada (1978b, 1982) and Vaid et al. (1989). Their tests were mainly intended to analyse the undrained behaviour of a loose sand, which had been previously subjected to liquefaction. In particular Ishihara and Okada (1978b, 1982) analysed the effects induced by a small and a large undrained preshear on samples which were not undergoing complete liquefaction; here "large" means a preshear to a maximum stress ratio greater than the one corresponding to the line of phase-transformation. On the other hand, Vaid et al. (1989) considered as "large" a preshear up to a stress ratio greater than the slope of the line connecting the stress state at peak deviator stress in a q - p' diagram (i.e. the instability line defined by Lade et al. 1988) and examined the effects induced by a large and a small undrained preshear on the slope of the instability line.

In the following, the effects induced by undrained preshear on moist tamped samples which undergo complete liquefaction are considered along both triaxial compression and extension undrained effective stress paths. Having loaded the samples under undrained conditions up to an axial strain of about 4% on the compression side (corresponding to a "large" preshear, as defined by Vaid et al., 1989), the drainage valve was opened and consolidation was allowed, as proposed by Ishihara and Okada (1978b, 1982); then the samples were subjected to a second undrained loading, both in compression and in extension. Care was taken to ensure similar void ratios at the beginning of the second undrained loading. The

Fig. 7. The effects induced by drained extension preshear on the anisotropy induced by a previous compression preshear

Fig. 8. The effects induced by undrained compression preshear on subsequent undrained compression and extension behaviour (where e_0 is the void ratio at the beginning of the undrained preshear and e is the void ratio at the beginning of the undrained loading)

results are shown in Fig. 8: the undrained compression preshear gives a large increase in the maximum deviator stress on subsequent undrained compression loading. The initial inclination of the undrained stress path is similar to the case of the virgin sample, so either the occurrence of the plastic strains is similar to the situation with the virgin samples or the elastic anisotropy induced is negligible. The overall effects of undrained preshear resemble those induced by a drained preshear along a stress path directed towards the negative p' -axis (Fig. 4).

These results can be compared with the findings reported by Vaid et al. (1989), who observed that, after an axial strain of 4% along an undrained compression preshear, a pluviated sand sample with an initial relative density of

$D_r=44.5\%$ (i.e. denser than the samples of Fig. 8 where $D_r=20-30\%$) changes the virgin contractive behaviour into dilative. This change was not observed in our experimental results and the difference is mainly due to the smaller initial density, but probably also related to the different sample preparation method.

Figure 8 also shows the effects of undrained compression preshear on the subsequent undrained extension loading: in this case the effects are small and similar to those induced by a drained compression preshear along a conventional compression stress path, as shown in Fig. 5.

The Effects of Drained Cyclic Compression Preshear

The effects induced by cyclic undrained preshear were

Fig. 9. The effects induced by drained cyclic compression preshear on undrained behaviour

analysed in detail by Vaid et al. (1989); this section briefly outlines the effects induced by a cyclic drained compression preshear. A sample was subjected to 16 cycles with the deviator stress varying between $q_{max}=100$ and $q_{min}=0$ kPa, and was then loaded under undrained conditions. The results are shown in Fig. 9 together with those obtained from a sample loaded to the same maximum deviator stress ($q_{max}=100$ kPa), then unloaded and finally reloaded under undrained conditions (i.e. presheared with only one load-unload cycle). In this way the maximum deviator stress applied during preshear is the same, whereas the axial strains induced by preshear are different: in fact cyclic preshear induces an increase in axial strain of about $\epsilon_a=0.5\%$. In a way, it is therefore possible to highlight the fraction of anisotropy induced by strain. Figure 9 shows that, although the results are not directly comparable with each other, because the void ratios at the beginning of the undrained loading phase are different ($e=0.91$ and $e=0.88$), the peak strength of the sample subjected to cyclic loading is about 15% greater than the other, whereas the initial elastic anisotropy does not seem to be affected by the cyclic preshear. The increase of maximum deviator stress is due partly to the different density ($D_r=26\%$ and $D_r=35\%$) and partly to cyclic loading and the latter portion can be considered as being strain-induced.

CONCLUSIONS

This paper presents a detailed analysis of the effects induced by drained and undrained preshear and, more in general, by preloading history on the undrained behaviour of loose Hostun sand samples prepared by moist tamping and tested in a triaxial cell with frictional basis. Unlike other studies on this topic, the experimental findings concern both drained and undrained preshear, along

different stress paths and up to different stress ratios, both in triaxial extension and in compression.

First, the meaning of the descending part of the undrained effective stress path is experimentally analysed, comparing the undrained effective stress paths with the position of the stress states in which a large reduction in the stiffness of the stress-strain behaviour occurs along drained stress paths applied to samples which had been subjected to the same preloading history. In this way, the analysis of undrained effective stress paths is shown to be an expeditious and reliable means for assessing the evolution of the shape of the yield surface of loose samples, especially on the same side as the previous preshear. Moreover, if a reverse in loading direction is applied, so that the behaviour can be considered initially elastic, the elastic anisotropy can also be deduced from the initial inclination of the undrained stress path. As a consequence, the results are mainly discussed from the point of view of understanding the evolution and the effects of stress-induced anisotropy on the shape of the yield surface and on the elastic anisotropy. Care was taken in order to have fairly similar initial void ratios at the beginning of each undrained loading.

The isotropic preconsolidation is first shown to increase the initial isotropy and to induce an enlargement of the yield surface, as already observed in the literature.

The drained compression preshear is shown to induce an important stretching of the yield surface and a considerable increase in the elastic anisotropy on the compression side, whereas the effects on the extension side are small. The maximum stress ratio reached during drained preshear is primarily responsible for the evolution of anisotropy, but the inclination of the stress path is also very important in the stretching of the yield surface.

In general, for the drained extension preshear the same

effects can be recognised as those induced by drained compression, though the elastic anisotropy caused by extension preshear on the extension side is much smaller.

The effects induced by undrained compression preshear on undrained extension and compression effective stress paths were analysed: on the compression side the yield surface appears to be enlarged, whereas on the extension side it seems virtually unchanged.

Finally, the effects induced by a drained cyclic compression preshear were studied. By comparison with a monotonic drained compression preshear, the cyclic preshear induces an increase of axial strain and thus the portion of strain-induced anisotropy emerged as having a key role.

These results represent a further improvement in the analysis of the effect of preloading history on the undrained behaviour of loose saturated sands and a preliminary step towards a better understanding of the evolution in the yield surface and elastic anisotropy induced by preloading history in loose sands prepared by moist tamping. Moreover, these findings could be useful for the formulation and calibration of constitutive models intended for capturing the evolution of mechanical anisotropy.

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